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Headquarters
National Aeronautics & Space Administration
Washington, D.C.

FINAL REPORT

STUDY OF CRATER EFFECTS IN LOW DENSITY SURFACES

Contract No. NASW-1196

Utah Research & Development Co., Inc.
1820 South Industrial Road
Salt Lake City, Utah 84104

801/486-1301

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INTRODUCTION

The purpose of the work done under Contract NASW-1196, "Crater Effects in Low Density Surfaces," has been to investigate the critical parameters which determine the shape and size of craters formed in low density materials. Interest in these characteristics arises from a consideration of materials which might be used for shielding spacecraft or for capturing meteoric debris. Also, these characteristics are of interest in studies of lunar surface properties.

The objective of the present phase of the contract has been to explore the possibility of capturing meteoric material during collisions involving meteorites and a low density surface. Analytical and experimental approaches to this objective are used to determine the effects which might be expected. The application of the results of this study could well have an effect on the analysis of the lunar surface properties.

This final report consists of summaries of the first three quarterly progress reports and a technical report describing the experimental work performed during this final report period.

SUMMARY OF WORK DONE PRIOR TO THIS REPORT PERIOD

Work done during the first quarter of the contract was described in the progress report covering the period 4 May to 4 August 1965. During this period, stainless steel, aluminum, magnesium, and nylon spheres were accelerated by a light-gas gun into targets of lightweight concrete, vesicular lava, pumice, and foamed glass. It was found that the cross section of the crater changed from a bottle shape to a cylindrical shape to a hemispherical shape as the target increased in density. The transition points of the crater shapes varied as a function of projectile density. As the density of the projectile increased, the target density at which a given transition occurred increased. The data were plotted in various ways to show these results.

Craters were formed with aluminum, steel, nylon, and magnesium projectiles in targets made of rigid and flexible polyurethane foams, foamed glass, and natural pumice as described in the progress report written in June 1966. The velocity range involved was 4.7 to 6.9 km/sec. Crater dimensions and volumes were determined. Values of shear strength and shearing energy were determined for all target materials. Some comparison was made of different projectile-target combinations to better understand the reasons for differences in crater shape. Values were determined for target mass displaced in a crater per unit of energy involved. It was found that projectiles of some materials are much more efficient in cratering than are others; steel projectiles being less efficient than the other types used by as much as a factor of two. Plots were made showing V/V_o and p/d being equal to $c\left[(\rho_p/\rho_t)(\rho_p v^2/S_t)\right]^b$ where b and c are constants, V is crater volume, V_o is projectile volume, p is crater depth, d is projectile diameter, ρ is density, v is projectile velocity, s is shear strength, and the subscripts p and t denote projectile and target. It was found that in the volume relationship, b remains constant at a value of 1/2 for each target material but c varies from 0.2 to 1.0. In the depth relationship, b is 1/3 for rigid targets and 1/2 for flexible ones, with c varying from 0.025 to 0.3.

Knowing that a projectile traveling at about 3 km/sec or faster normally disappears at impact, it seemed of interest to determine what becomes of the projectile. If some of the projectile remains in the target in a very dissociated form, the analysis of the craters in a spaceship hull might be used to determine the flux density of small iron and stony meteors. For this study, 1/8-inch diameter steel balls, each activated with about 10 microcuries of neutron-induced radioactivity were used. Fragments as small as 10^{-4} part of one ball mixed with 10 cc of debris were easily detected with a crystal scintillation counter. These balls were impacted against targets of different materials and the resulting craters examined to determine the amount of radioactivity present. The fraction of projectile material remaining in each crater was thus determined.

It was found that iron projectiles are retained in a mass of very high purity aluminum at impact velocities up to 6 km/sec. According to the Bjork theory, the physical processes in the impact do not change radically up to 30 km/sec or faster. Thus, it seems reasonable that a meteor can be retained by a pure aluminum spacecraft skin. The meteor, if it is there, will be dispersed in a much larger mass of aluminum; but since the aluminum is to be very pure, a small added impurity of stony matter or iron can be detected by neutron activation analysis or by chemical analysis. In this way, a section of soft, pure aluminum skin on a satellite left in space for some years and then recovered might yield valuable evidence as to the prevalence of stony or metallic meteors in the one to one-hundred-micron size range. It was found that hard aluminum does not demonstrate the characteristic of capturing an impacting projectile. This is unfortunate since the alloys of aluminum, such as 24ST, are commonly used for spacecraft skins.

The experiments showed that steel balls at 6 km/sec were stopped intact in low density foam. There are theoretical reasons to believe that this cannot occur at a slightly higher projectile velocity. The projectile should be melted by friction with the medium. At meteor velocity, the projectile should be vaporized. The results of low velocity tests should not be extrapolated to this situation. No information was obtained from which to predict whether a vaporized meteor will be deposited in a cavity in a foam meteor bumper or escape through its entrance hole. One might hazard a guess that the meteor will escape with fragments of a brittle foam, and be retained by elastic foam, in line with the results of shooting 6 km/sec steel balls into pumice and dense polyurethane foam.

In the period covered in the progress report dated May 1967, an effort was made to define limits to be applied to the experimental work to follow. This attempt to arrive at some sort of analytical expression that could describe quantitatively the amount of debris that might be generated in the process of impact between a high speed projectile and a low density target was quite discouraging. Very little empirical work has been published in the area of low density impact. There is virtually no work reported on mass of the projectile which is captured except for the work done by URDC under this contract. The principal sources of information come from the work of Palmer and Turner[1] and Gault, et al.[2] Both of

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[1] Turner, Gerry H. and Palmer, E. Paul, "Energy Partitioning in High-Velocity-Impact Cratering in Lead," Part I of Final Report on Contract AF 04(694)-259, Technical Report UU-14, May 1964 for Ballistic Systems Division, Air Force Systems Command, Norton Air Force Base, California.

[2] Gault, Donald E., Shoemaker, Eugene M., and Moore, Henry J., "Spray Ejected from the Lunar Surface by Meteoroid Impact," NASA Technical Note D-1767 by Ames Research Center, Moffett Field, California

these groups worked on the problem of partitioning of energy in the impact process and have obtained results that are worthwhile.

There has been much work done in determining the amount of mass removed from metallic and earth materials by impact and explosion. Figure 1 shows the mass removed from the crater area per Joule of energy for rock and sand in one extreme and lead in the other extreme. Most metals fall between these curves. Foamed glass targets show a value of 3×10^{-3} gms/Joule, which falls close to lead; while the value of 2×10^{-3} gms/Joule for rigid polyurethane foams is a little less than lead. The results on the lead targets seem anomalous since lead craters are large compared with other metals. The data used for the lead curve is not the mass of the crater, but rather the mass of the material which actually leaves the target as measured by weighing the target before and after impact. This value is approximately one-tenth of the mass represented by the crater volume. The remaining nine-tenths of the crater material is displaced lead.

The process of removing material from the impact zone in low density targets may well be similar to the removal process in lead. The compressive strength of a low density target is low and material from the crater zone may be displaced permanently and be represented as a slight local increase in density at points somewhat distant from the impact area. Pictures that have been taken of the actual impact process show very little spray or ejecta from low density targets when compared with metallic target impact. These results could be due to the "pear shape" of the crater. A crater of this shape tends to trap ejecta. This effect could be enhanced by the low compressive strength of the target which would allow the material to be permanently displaced. Since the value for the mass of the target lost per unit energy as shown in Figure 1 is calculated from crater size rather than by weighing the target, an upper limit of the mass lost is given by the curves for glass and rigid polyurethane in Figure 1. It is possible that one-tenth of the value of the curve, or approximately 2×10^{-4} gms/Joule would be more appropriate.

Low density projectiles have not been considered in the discussion thus far. The work which was reported by Cannon and Turner[3] as part of this contract shows a definite effect on the target mass lost due to different projectile materials. It is not clear how much of the observed difference in results is due to projectile strength and how much is due to mass.

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3 Cannon, Emerson T. and Turner, Gerry H., "Cratering in Low Density Targets," Technical Report under Contract NASW-1196 for NASA, February 1967.

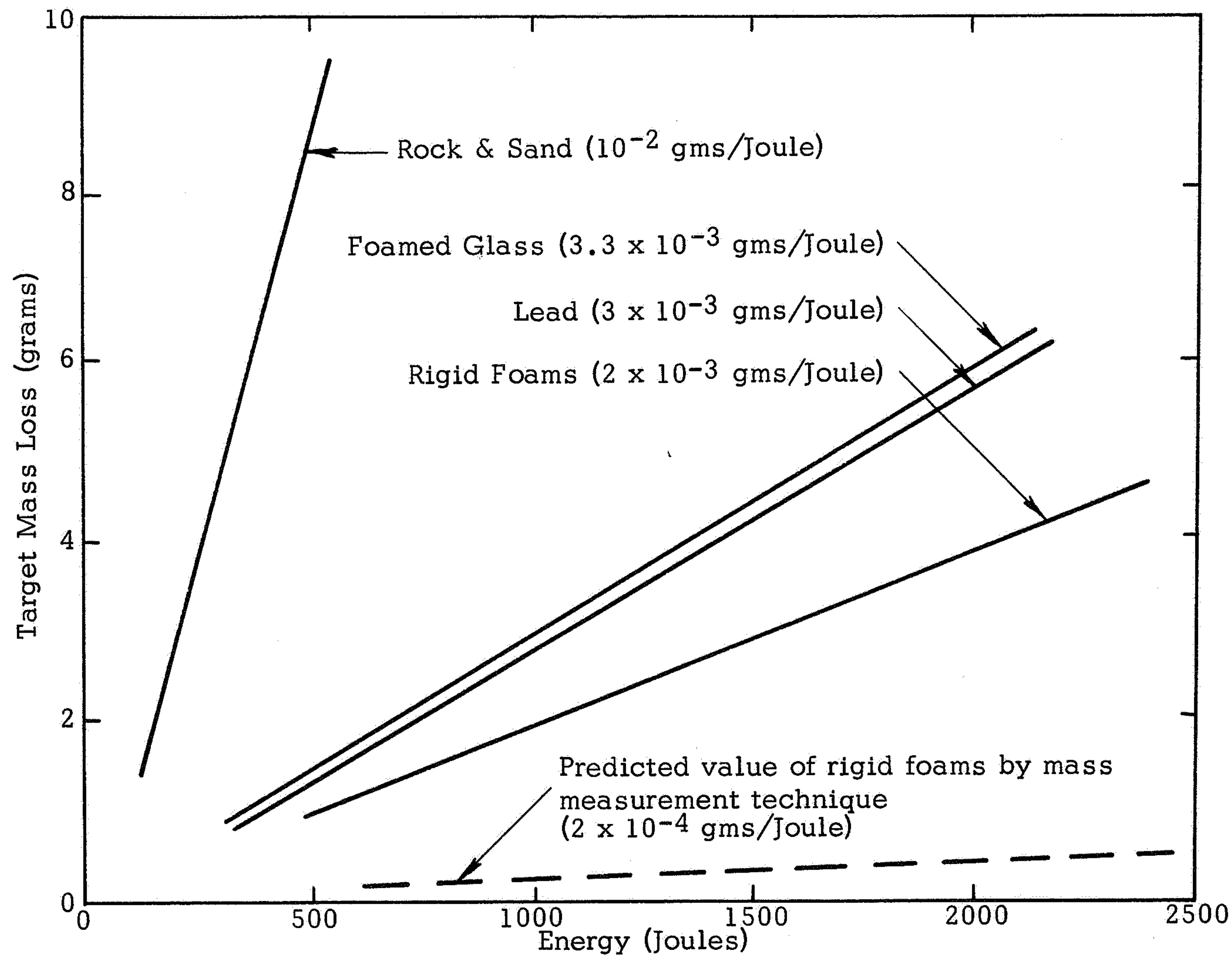

Figure 1. Target Mass Loss vs Projectile Energy for Several Types of Target Material

SUMMARY OF WORK DONE DURING THIS REPORT PERIOD

A light-gas gun was used to accelerate 3/16-inch diameter, gold-impregnated, epoxy projectiles to velocities of about 6 km/sec. These projectiles were impact into targets of lead, hard and soft aluminum, and rigid polyurethane foams of various densities.

Some of the projectiles were activated in a nuclear reactor. Craters formed with these projectiles in both the metals and the foams were analyzed with a crystal scintillation counter to see how much of the projectile remained in the target. It was found that only about two percent remained in the lead and hard aluminum targets and between 30 and 40 percent in the soft aluminum ones. In the foams, it was found that the fraction of projectile left in the crater is inversely proportional to target density. Values obtained ranged from 55 percent with targets having a density of 0.03 gm/cm^3 down to four percent with targets of 0.36 gm/cm^3 density.

All of the foam targets were sectioned and the parameters of the craters were determined. A photograph is included to show cross sections of craters formed in foams of different densities.

Experiments were performed to measure the energy, velocity, and mass of material ejected from craters formed in the foams. The total energy of the material was measured by catching it in a lead enclosure called a "trap," determining the change in temperature of the trap, and relating this temperature change to energy. Energy associated with a fraction of the material coming from the crater over five-degree angular segments was measured by isolating the material with a shield having a hole in it of the proper size and shape and then catching this material in a trap. In a similar manner, material was isolated and its average velocity was measured by catching it in a ballistic pendulum. A series of traps positioned at various angles to the target were used to catch material in order to determine the angular distribution of mass.

The results of these experiments show that most of the ejected material leaves the target at angles, measured relative to its surface, of from 40 to 60 degrees. Most of the energy associated with this material also is found at these angles. The average velocity of this material is relatively low, with little indication that a significant amount of material has a velocity above 1 km/sec.

EXPERIMENTAL METHODS

Gun and Projectiles

A light-gas gun was used to accelerate 3/16-inch diameter, gold-impregnated, epoxy projectiles to nominal velocities of 6 km/sec. These projectiles were made by mixing one part by weight of minus 325 mesh gold powder with three parts of epoxy. The epoxy was a two-part putty-type called Epoxybond. Its tensile strength was specified as 1700 lb/in^2 and its compressive strength as 9600 lb/in^2. The density of the epoxy alone was about 1.9 gm/cm^3 and of the gold-filled epoxy about 2.5 gm/cm^3. Each projectile weighed about 0.140 gram.

Targets

Four different types of target material were used: lead, soft aluminum (1100), hard aluminum (24ST), and rigid polyurethane foams of various densities. The foams were supplied by Goodyear at no cost. The densities of the foams were calculated from the volumes and weights of uniformly shaped specimens. The average values of the different densities were 0.03, 0.05, 0.10, 0.17, and 0.36 gm/cm^3.

The shear strength of each target material was determined. This was done by measuring the maximum force necessary to shear a one-inch diameter plug from a specimen. The energy used in shearing the specimen was calculated for each test by plotting force as a function of distance traveled by the die, and then calculating the area under the curve. Values were determined for two different energy relationships; energy per unit area used in shear up to the point of maximum stress, defined as the yield point, and energy per unit area used in shear during the entire punching operation. Actual values obtained are shown in Figures 2 and 3. Figure 2 shows shear strength as a function of material density, and Figure 3 shows energy used in shear as a function of material density. These results agree quite well with those obtained with similar foams in previous work.

Crater Measurements

Crater dimensions were determined by cross-sectioning the targets. Crater volumes were calculated from measurements of these cross sections at intervals along the axis of the crater. Because the diameter of each crater was not constant, it was necessary to consider average values for a number of segments in each crater when calculating its volume.

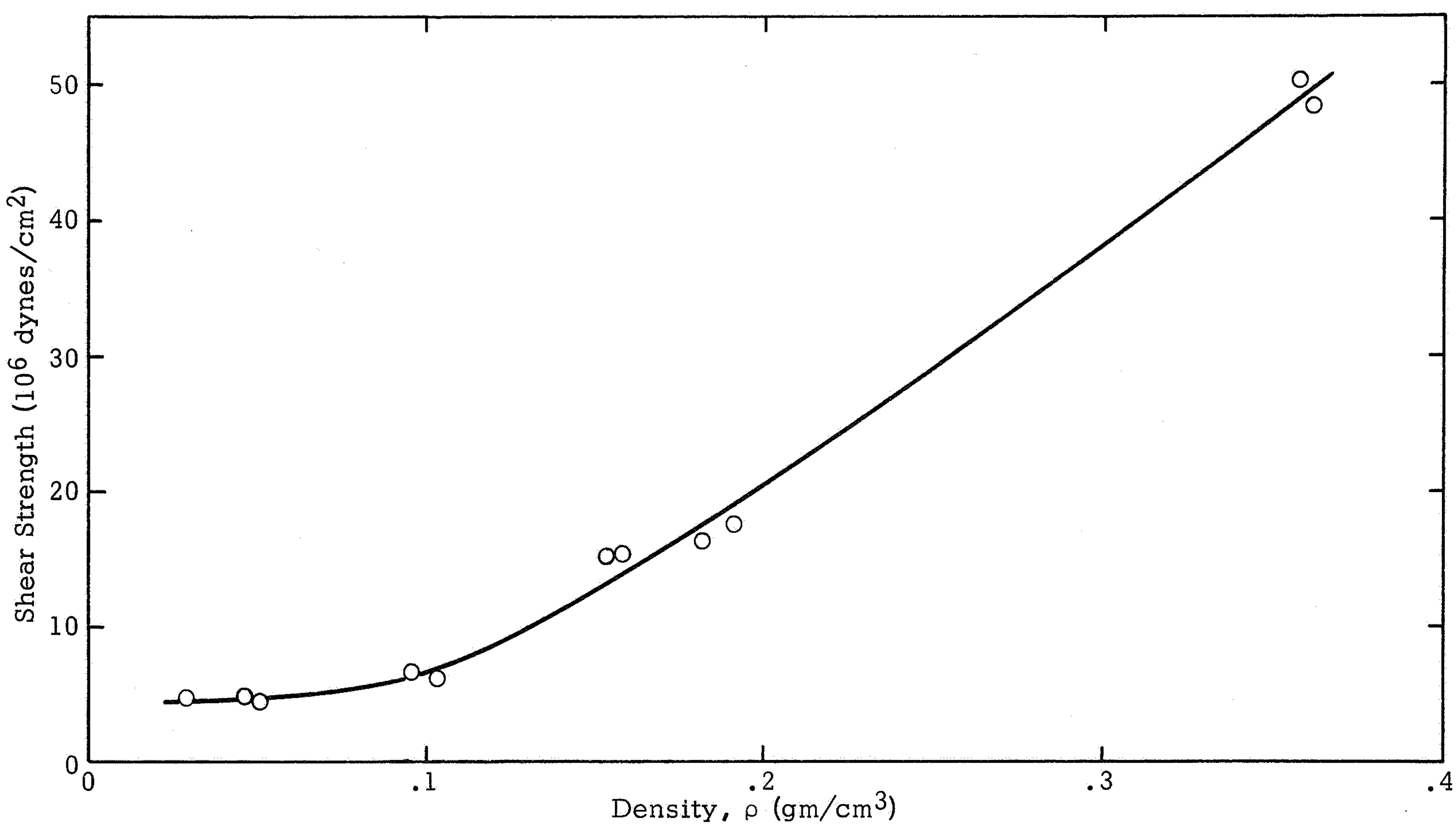

Figure 2. Shear Strength as a Function of Density for Rigid Polyurethane Foams

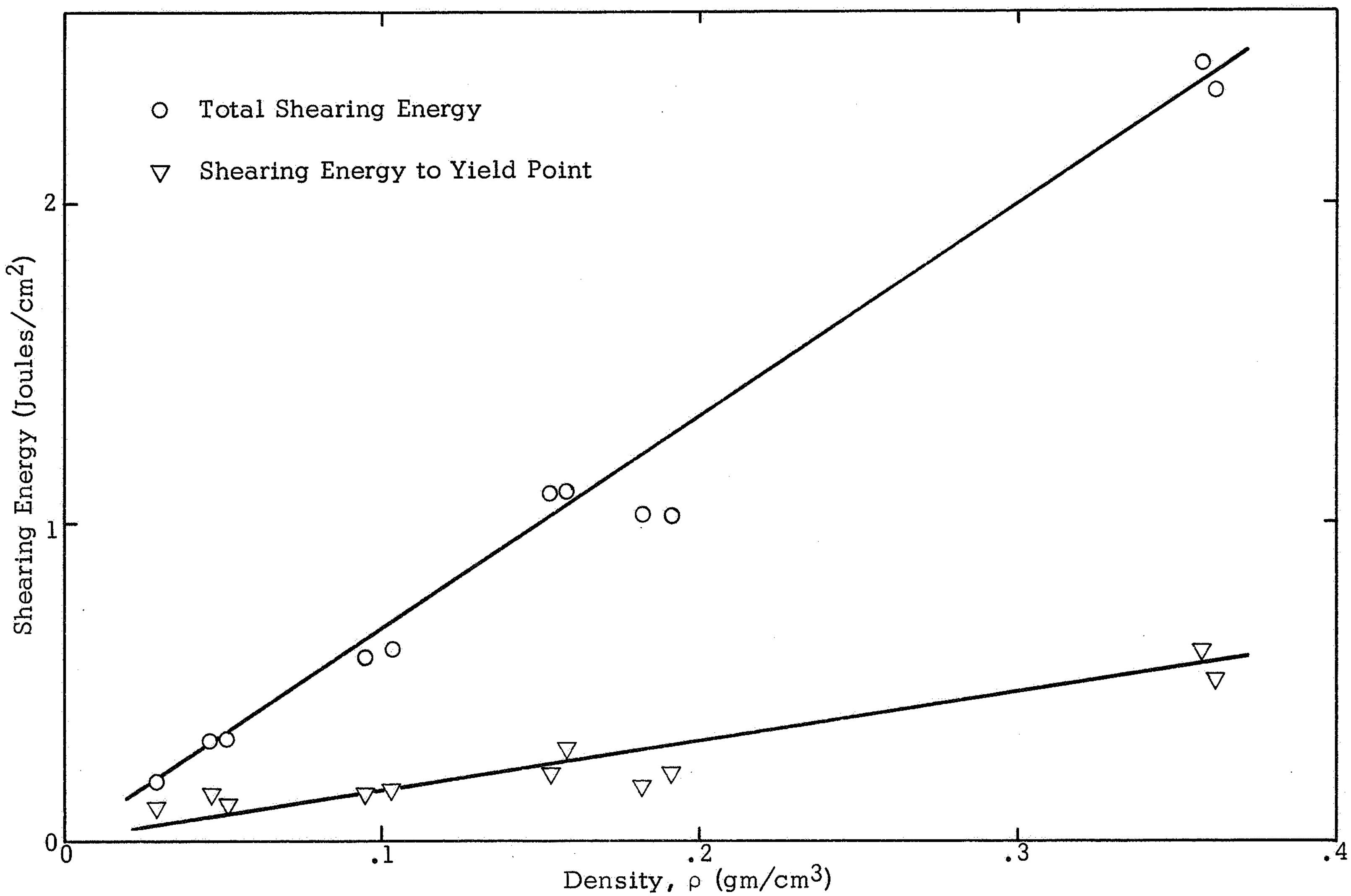

Figure 3. Shearing Energies as Functions of Density for Rigid Polyurethane Foams

Radioactivity Measurements

Gold-filled epoxy balls were irradiated in the nuclear reactor at the University of Utah for about six hours. This induced about 0.1 microcurie of radioactivity in the gold in each ball. Craters were formed with these balls in targets of lead, soft and hard aluminum, and each of the foams. A crystal scintillation counter was used to measure the amount of radioactivity associated with each crater. This value, when compared with total radioactivity of the ball before firing, indicated the fraction of the ball remaining in the crater.

The radioactivity measurements could be made directly on the craters formed in metal targets. The craters in the foams were so large, however, that it was necessary to reduce the volume of material being analyzed. This was done by charring the foam by heating it at about 500° F for one hour and then pulverizing the residue with a mortar and pestle.

The radioactivity of the ball, and probably the characteristics of the radiation counter, were changing with time. For this reason, all measurements were made by comparing the activity of the ball material in the crater with that of a complete ball. This was done by positioning the ball material in the crater or pulverized foam ash a few inches from the detector and considering it as a point source; then the increase in counting rate was observed when a complete ball was placed in the crater or residue.

Gamma disintegrations were primarily considered in this work. However, some observations were made of Beta decay with the metal targets.

Measurements of Energy of Material Ejected from Craters

The sum of the kinetic and thermal energies associated with material ejected from a crater, called spray particles, at the time of its formation was determined using a method developed by Turner and Palmer[1]. This consisted of catching ejected material in a lead container called a "trap," and then observing the change in temperature of the trap. This temperature change was measured using a Keithley Model 150-B microvolt meter to indicate the voltage change in an iron-constantan thermocouple embedded in a wall of the trap. This output voltage was plotted as a function of time and the cooling portion of the curve was extrapolated back to zero time to get the maximum output. This output was converted to a temperature change by using a factor of 50 microvolts/°C. The temperature change was relative to a reference junction placed in an identical trap separated thermally from the trap being heated.

Two types of traps were used: one for catching all of the spray particles ejected from the crater, and one for catching only those spray particles ejected over a predetermined angular segment. Figure 4 is a sketch showing the arrangement used in measuring total spray particle energy. Figure 5 shows a typical plot of thermocouple output voltage as a function of time for this type trap. The arrangement shown in Figure 6 was used to measure angular spray particle energy. A shield with a hole of a proper size and shape in it was placed in front of the trap. This allowed only a certain fraction of spray particles coming from the crater over a five-degree angular range between angles θ_1 and θ_2 to enter the trap. It was assumed in this type of measurement that all spray particles entering the trap remained in it and that no secondary particles were ejected from it.

Measurements of Velocity of Material Ejected from Craters

A special ballistic pendulum was built to measure the average velocity of a fraction of spray particles ejected from a crater. This device is shown in Figure 7. It consisted of a frame in which a spray particle trap could be supported and which was suspended by four strings. A fraction of the spray particles ejected at specific angles of interest were isolated with a shield with a hole in it of the proper size and shape. These spray particles caused the pendulum to swing as they were caught by the trap. As the pendulum was displaced a small wire attached to it would make contact with a series of metal strips which were connected in series with electrical resistors. A voltage was applied across these resistors and a measuring circuit, using an oscilloscope, was formed through the pendulum. The amplitude of the swing of the pendulum was determined from an oscillogram showing a series of voltage steps as the contact wire moved from one metal strip to the next. The momentum of the spray particles was calculated from the displacement of the pendulum, its weight, and its effective length.

The trap was accurately weighed before and after each shot to determine the mass of the spray particles caught in it. This value, when used with the momentum value, gave the average velocity of the spray particles caught in the trap. It was assumed in making this determination that the impact of the spray particles in the trap was inelastic with no material being lost from the trap.

Measurements of Spray Particle Mass

The mass of spray particles ejected from a crater was determined in two ways. First, the total mass of material originally in the crater region was calculated by multiplying the measured crater volume by the target density. Second, a series of eight small traps was used to catch spray particles coming from the crater at different angles. These traps were cylindrical in shape, were

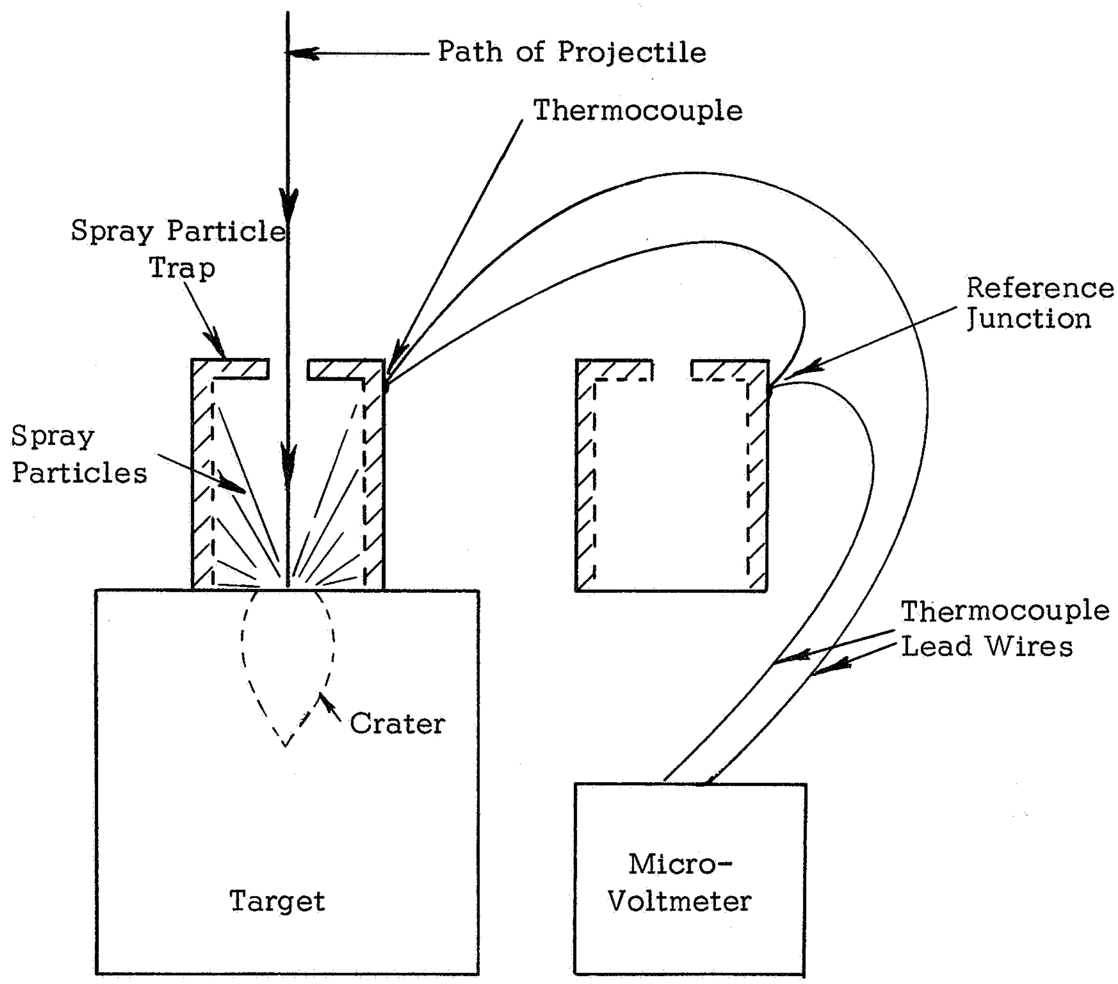

Figure 4. Arrangement Used in Measuring Total Spray Particle Energy

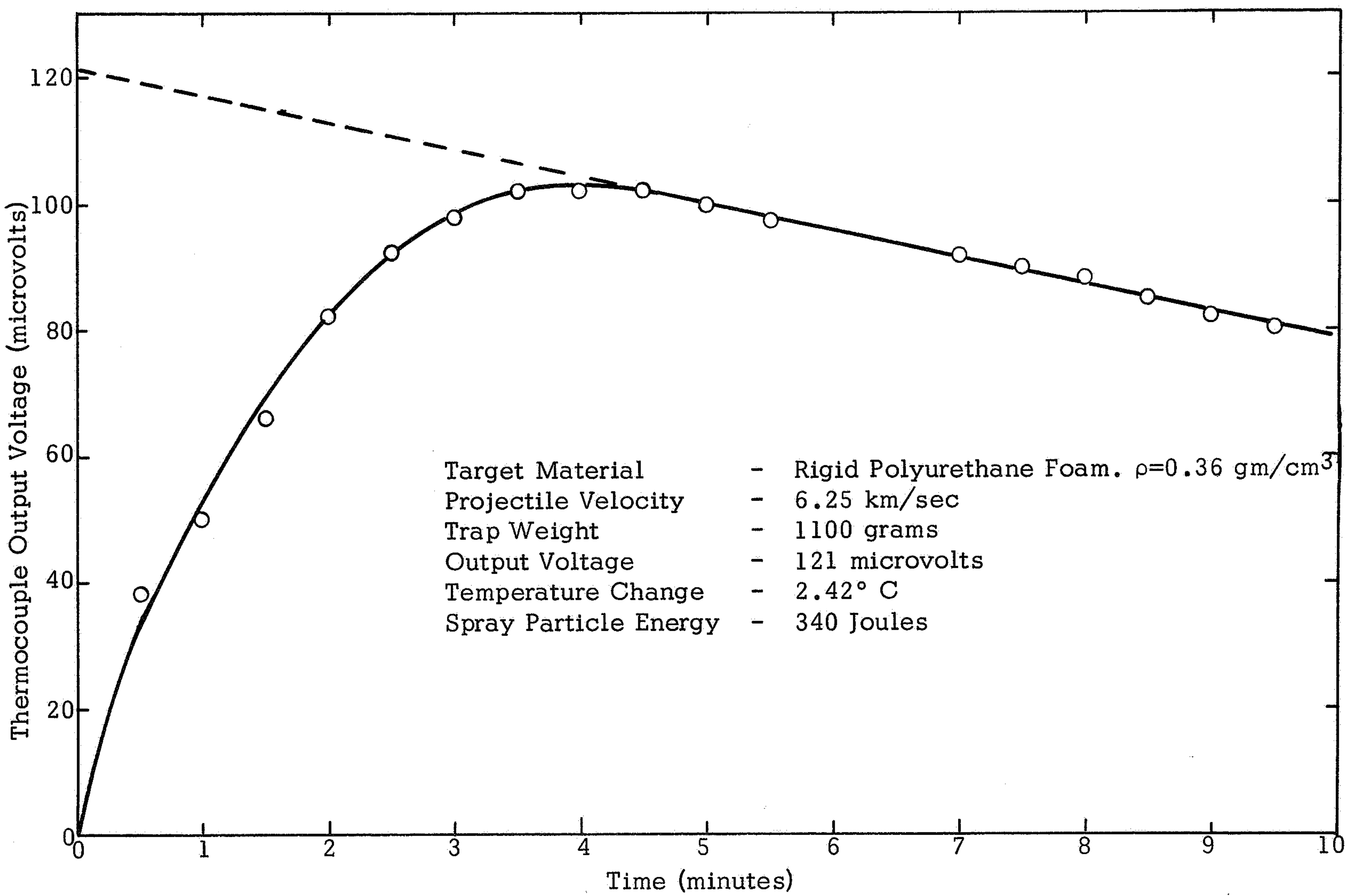

Figure 5. Thermocouple Output Voltage as a Function of Time for a Shot in Which All Spray Particles were Caught

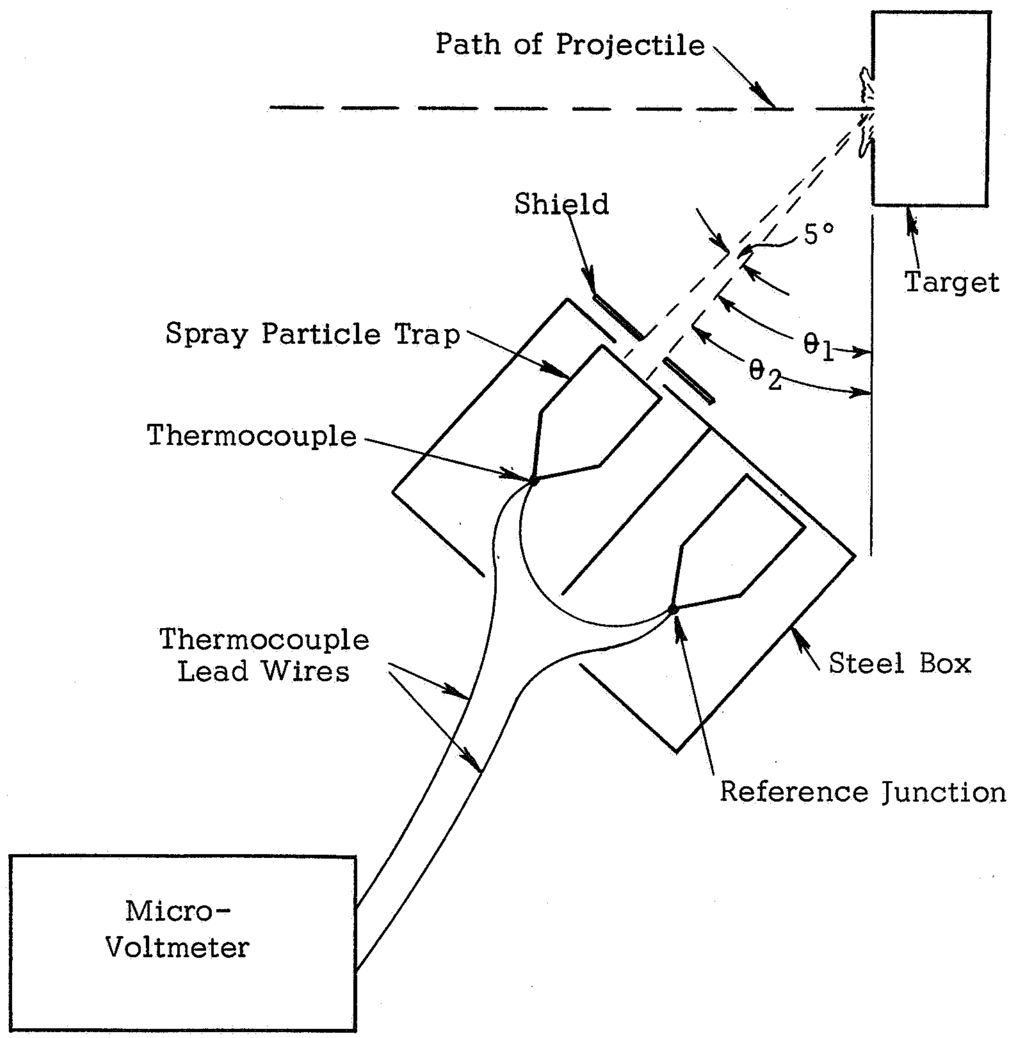

Figure 6. Arrangement Used to Measure Angular Spray Particle Energy

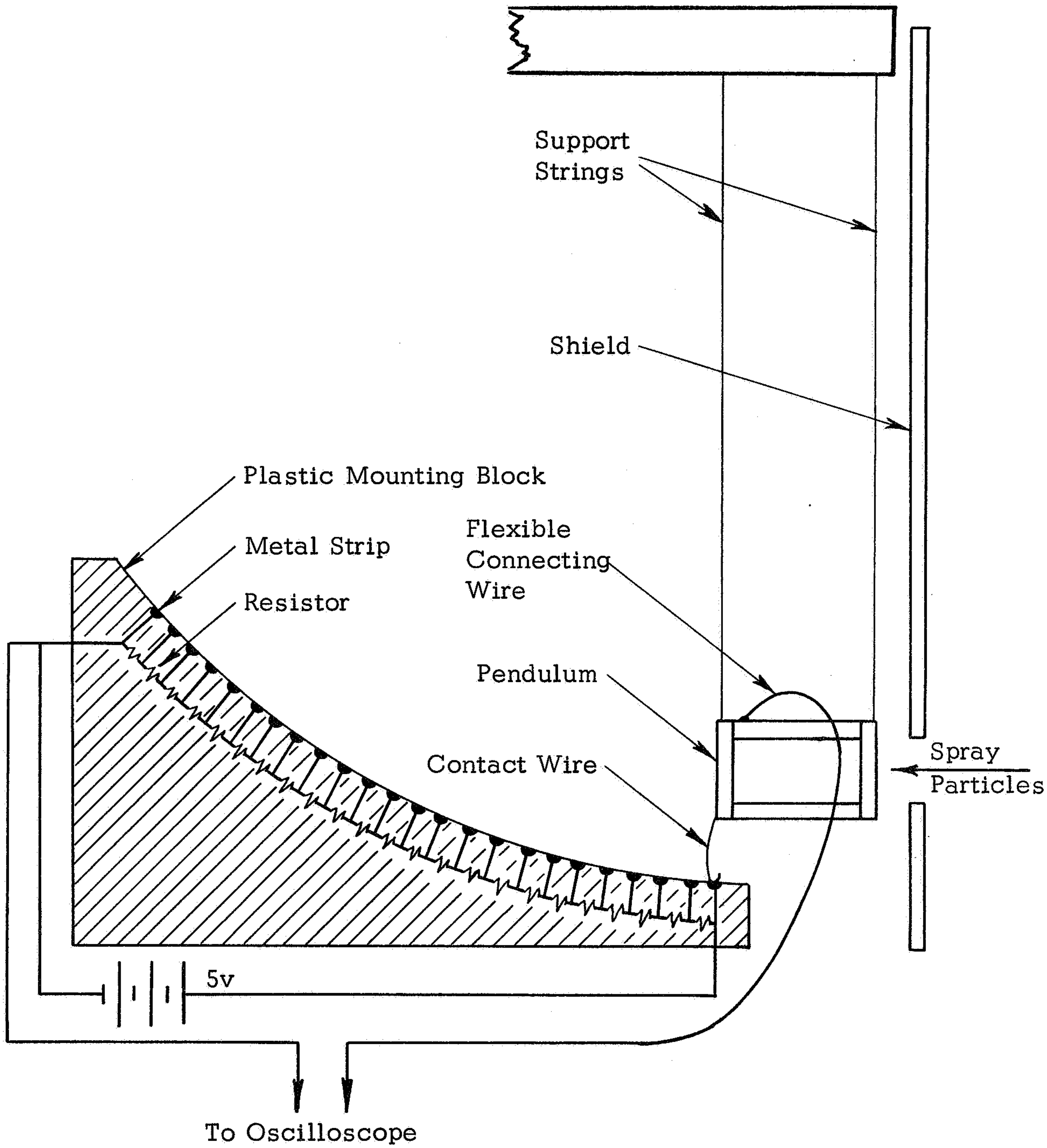

Figure 7. Ballistic Pendulum Arrangement Used in Catching Spray Particles and Measuring Their Average Velocity

mounted in a holder that could be placed in the correct position relative to the target, and were covered with a metal shield which isolated spray particles leaving the target at known angles. A sketch of the arrangement is shown in Figure 8. The traps were weighed before and after the shot to determine the mass of material caught.

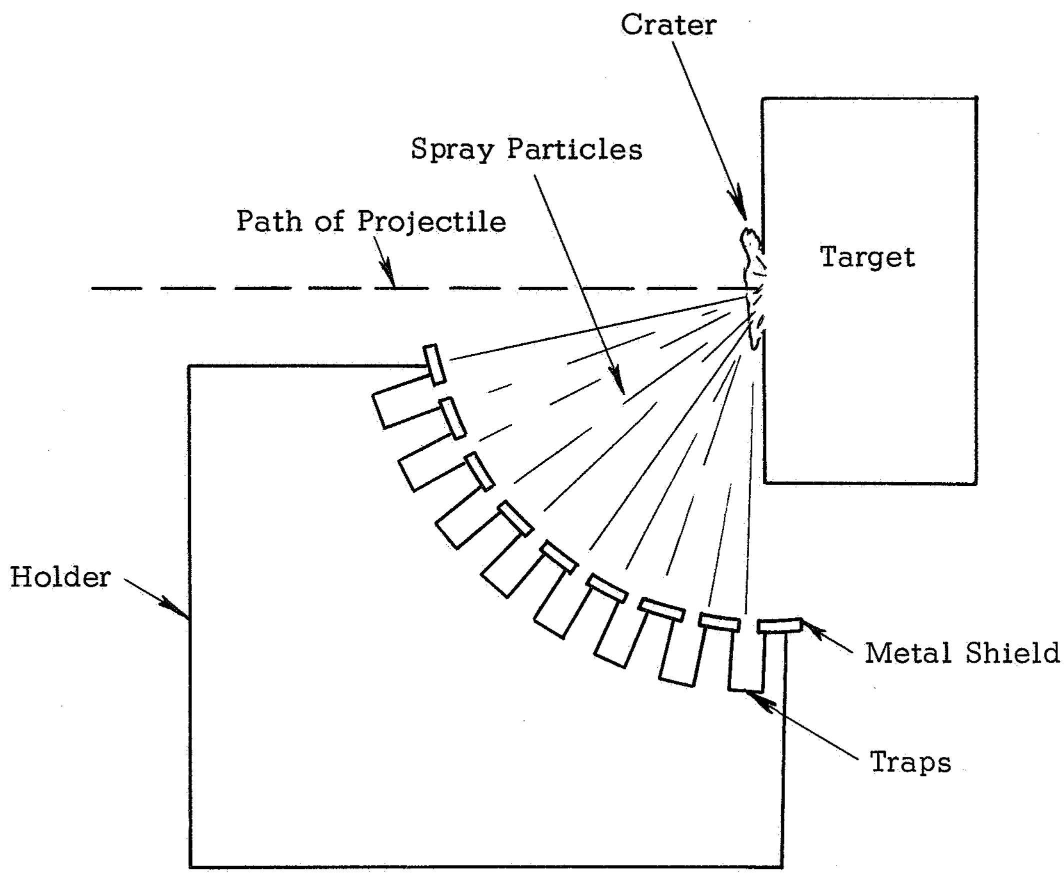

Figure 8. Arrangement Used to Catch Spray Particles Coming from a Crater at a Number of Different Angles

EXPERIMENTAL RESULTS

The results of the various experiments are listed in both tabular and graphical form. Considering the complexity of the experiments, good agreement was generally found in the results. The greatest variations occurred among data obtained by isolating a fraction of the total spray particle material. These variations can be explained somewhat by the fact that ejected material is not uniformly distributed around the periphery of the crater as it leaves the target. Observations have been made of this effect and the term "ray" is used when reference is made to such concentrations of material.

Capture of the Projectile by the Target

Data concerning the fraction of the projectile remaining in metal targets, as determined with radioactive epoxy-gold balls, are shown in Table I. These data show that lead and hard aluminum retain very little of the projectile under these conditions while soft aluminum retains a considerable amount. These results agree generally with those reported previously where radioactive steel projectiles were used.

TABLE I. DATA CONCERNING THE FRACTION OF THE PROJECTILE REMAINING IN METAL TARGETS IMPACTED WITH 3/16-INCH DIAMETER RADIOACTIVE, EPOXY-GOLD BALLS

Shot Number	Target Material	Weight of Projectile (gram)	Projectile Velocity (km/sec)	Fraction of Projectile in Crater
346	Lead	0.150	6.25	0.026
347	Lead	0.143	6.08	0.027
348	24ST Al	0.140	6.15	0.010
349	24ST Al	0.136	6.19	0.020
351	1100 Al	0.140	6.25	0.300
352	1100 Al	0.143	6.13	0.370

The values shown in Table I for the fraction of the ball left in the crater were obtained from gamma-ray counts. An interesting observation was made of the crater from shot number 351 by considering beta-ray counting rates. It was determined from gamma rays, that 30 percent of the ball was left in the crater. Beta rays showed that 27 percent of the ball was in the crater. Considering the fact that essentially all of these beta rays can be stopped by one millimeter of aluminum, this shows that nearly all of the projectile material in this crater is much less than one millimeter from the surface. This is the usual situation in hypervelocity impact where the projectile is found on the crater surface and not deep in the target.

Data concerning rigid polyurethane foams are given in Table II. Figure 9 is a log-log plot showing the fraction of the projectile remaining in the crater as being inversely proportional to the density of the target material.

TABLE II. DATA CONCERNING THE FRACTION OF THE PROJECTILE REMAINING IN RIGID POLYURETHANE FOAM TARGETS IMPACTED WITH 3/16-INCH DIAMETER, RADIOACTIVE EPOXY-GOLD BALLS

Shot Number	Target Density (gm/cm^3)	Weight of Projectile (gram)	Projectile Velocity (km/sec)	Fraction of Projectile in Crater
357	0.03	0.139	6.52	0.55
356	0.05	0.134	6.45	0.30
360	0.05	0.140	6.15	0.34
353	0.10	0.137	6.25	0.22
355	0.17	0.136	6.19	0.06
358	0.17	0.136	5.91	0.05
354	0.36	0.138	6.40	0.05
359	0.36	0.134	5.95	0.04

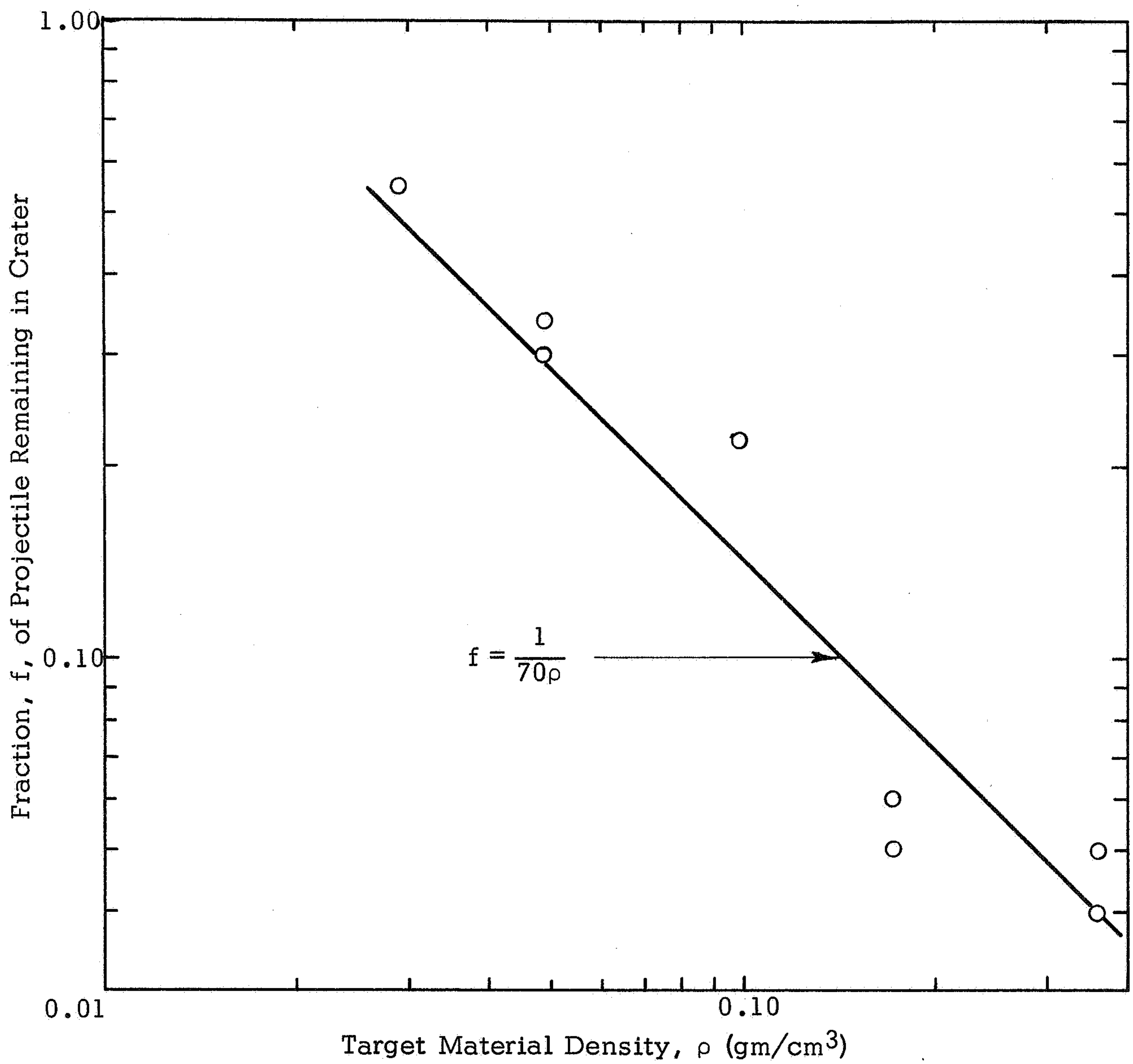

Figure 9. Fraction of the Projectile Remaining in the Crater as a Function of Target Material Density

Craters from two shots were examined to see where, within the crater, projectile material was deposited. This was done by sectioning the target into four equal parts along the depth of the crater and determining the fraction of the ball in each part. The results are given in Table III. They show that the bulk of the projectile material was found in the lower half of the crater and that the ratios of the fraction of ball in a section to the fraction in the whole crater are about the same for each crater.

TABLE III. DATA SHOWING THE FRACTION OF THE PROJECTILE LEFT IN DIFFERENT PARTS OF THE CRATER. SECTION 1 IS THE UPPER ONE-FOURTH OF THE TARGET, ETC.

Shot Number Target Density	360 0.05		358 0.17	
	Fraction of Ball in Section	Fraction in Section / Fraction in Crater	Fraction of Ball in Section	Fraction in Section / Fraction in Crater
Section 1	.02	.06	.006	.12
2	.06	.18	.008	.16
3	.18	.53	.021	.42
4	.08	.23	.015	.30
Total in Crater	.34	1.00	.050	1.00

Crater Shapes

A photograph of cross section of craters formed in each of the five foams of different densities is shown as Figure 10. This photograph shows that each crater is smaller in diameter at the target surface than it is at a point farther into the target. This was found to be the case for all shots. Data concerning crater measurements are given in Table IV. Crater depth is shown plotted as a function of target density in Figure 11. The data can be approximated by a curve having the equation $d = 3\rho^{-2/3}$ indicating that crater depth is inversely proportional to target density to the two-thirds power.

Cratering Efficiency

Cratering efficiency is defined as the mass of target material displaced by the crater per unit of kinetic energy of the projectile. Data for foam targets

Shot No.	395	370	373	367	379
Density (gm/cm^3)	0.03	0.05	0.10	0.17	0.36

Scale in cm

Figure 10. Photograph of Cross Sections of Craters Formed in Rigid Polyurethane Foams of Various Densities

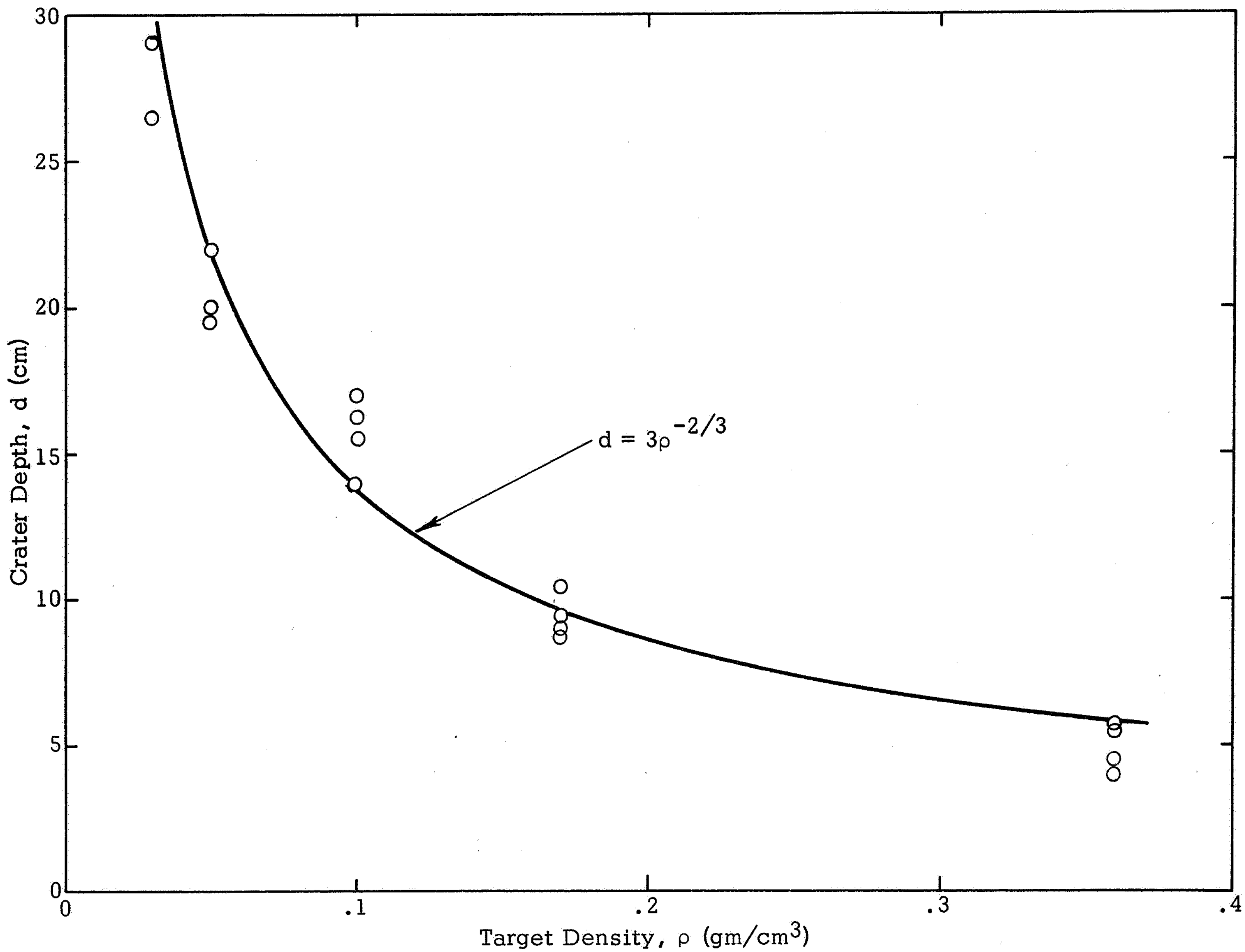

Figure 11. Crater Depth as a Function of Target Density for Rigid Polyurethane Foams

are given in Table V. Figure 12 shows cratering efficiency plotted as a function of target density. The curved line drawn through the data points is intended only to approximate average values.

TABLE IV. MEASUREMENTS OF CRATERS FORMED IN RIGID POLYURETHANE FOAMS OF DIFFERENT DENSITIES BY THE IMPACT OF 3/16-INCH DIAMETER EPOXY-GOLD PROJECTILES

Shot Number	Target Density (gm/cm^3)	Projectile Mass (gram)	Projectile Velocity (km/sec)	Crater Depth (cm)	Crater Diameter At Surface (cm)	Crater Diameter Maximum (cm)	Crater Volume (cm^3)
371	0.03	0.138	5.70	29.0	3.0	4.7	286
395	0.03	0.144	5.95	26.5	2.6	3.4	198
370	0.05	0.134	5.95	22.0	1.6	3.0	116
392	0.05	0.140	5.76	19.5	2.2	3.6	124
393	0.05	0.140	6.00	20.0	2.2	3.2	109
372	0.10	0.143	5.67	17.0	2.6	3.6	107
373	0.10	0.139	6.05	14.0	2.2	3.4	83
375	0.10	0.143	5.50	15.5	2.8	3.5	102
387	0.10	0.140	5.95	16.2	2.0	3.6	104
390	0.10	0.141	6.20	14.0	2.2	3.6	103
367	0.17	0.137	6.45	8.7	2.8	4.0	62
376	0.17	0.141	6.71	10.5	2.8	4.0	83
384	0.17	0.143	6.15	9.0	2.0	3.5	55
386	0.17	0.140	5.95	9.5	2.0	3.0	49
361	0.36	0.148	6.25	4.0	1.5	2.3	12
365	0.36	0.143	6.04	5.7	1.5	2.3	12
379	0.36	0.140	5.85	5.5	2.1	2.4	12
380	0.36	0.139	6.00	4.6	1.6	2.1	9
382	0.36	0.141	6.25	4.5	1.6	2.2	12
396	0.36	0.140	5.61	4.5	2.0	2.2	11

TABLE V. DATA CONCERNING CRATERING EFFICIENCY FOR THE IMPACT OF 3/16-INCH DIAMETER EPOXY-GOLD BALLS INTO RIGID POLYURETHANE FOAMS OF VARIOUS DENSITIES

Shot Number	Foam Density (gm/cm^3)	Mass Displaced by Crater (grams)	Projectile Kinetic Energy (Joule)	Cratering Efficiency (gm/Joule)
371	0.03	8.3	2280	3.6×10^{-3}
395	0.03	6.3	2510	2.5
370	0.05	5.7	2370	2.4
392	0.05	6.1	2320	2.6
393	0.05	5.3	2520	2.1
372	0.10	10.6	2300	4.6
373	0.10	8.3	2540	3.3
375	0.10	10.1	2170	4.7
387	0.10	10.3	2470	4.2
390	0.10	10.2	2710	3.8
367	0.17	10.6	2840	3.8
376	0.17	14.1	3180	4.4
384	0.17	9.4	2700	3.5
386	0.17	8.3	2470	3.4
361	0.36	4.2	2890	1.5
365	0.36	4.3	2600	1.7
379	0.36	4.3	2400	1.8
380	0.36	3.3	2500	1.3
382	0.36	4.2	2750	1.5
396	0.36	3.9	2200	1.8

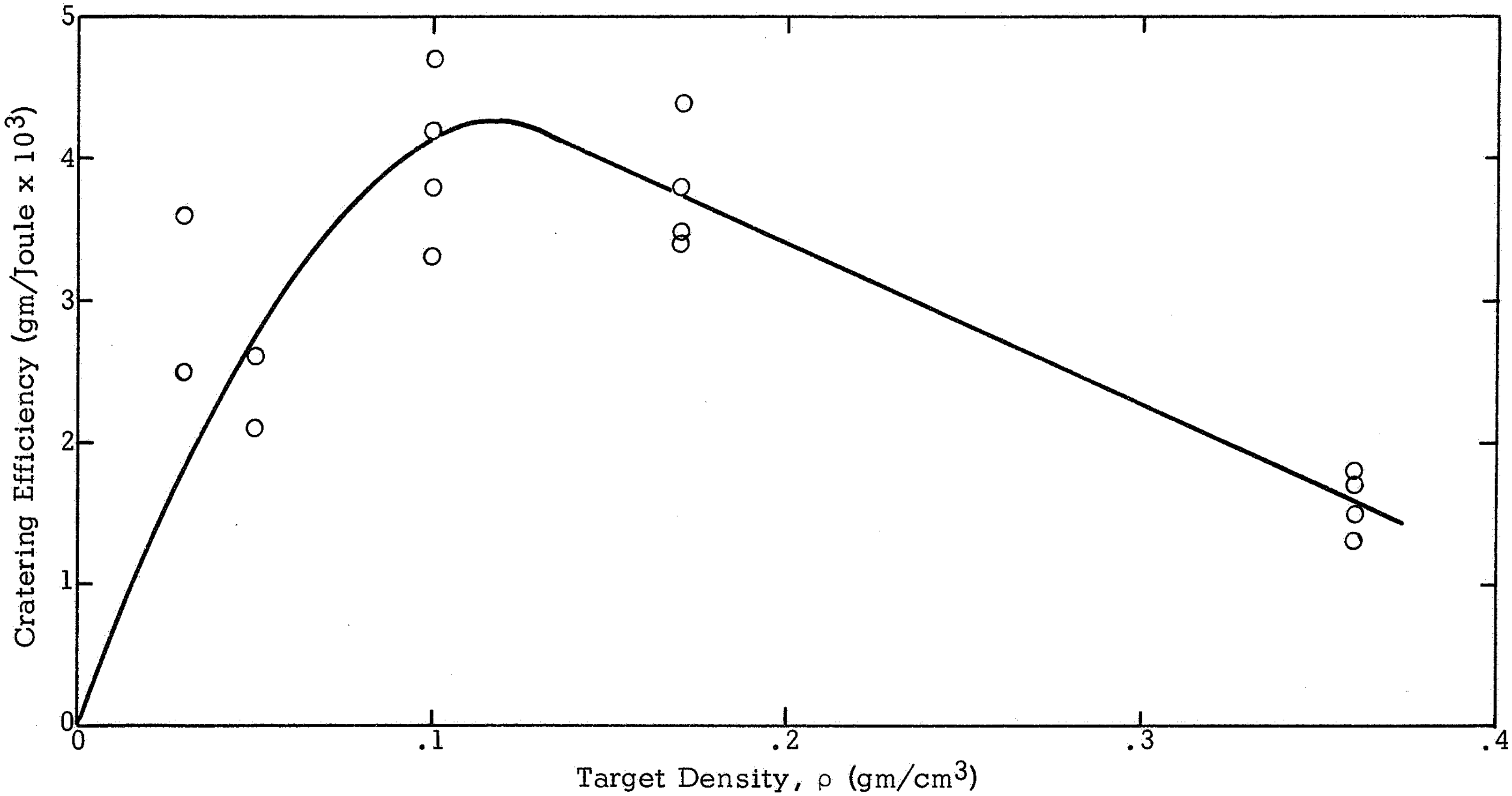

Figure 12. Cratering Efficiency as a Function of Target Density for Rigid Polyurethane Foams

Energy of Ejected Material

Total spray particle energy was measured in seven shots. Data concerning these shots are listed in Table VI. The ratio of total spray particle energy to the kinetic energy of the projectile is shown plotted as a function of target density in Figure 13.

TABLE VI. DATA CONCERNING TOTAL SPRAY PARTICLE ENERGY FOR THE IMPACT OF 3/16-INCH DIAMETER EPOXY-GOLD PROJECTILES INTO RIGID POLYURETHANE FOAMS OF VARIOUS DENSITIES

Shot Number	Target Density (gm/cm^3)	Projectile Kinetic Energy, E_k (Joules)	Total Spray Particle Energy, E_s (Joules)	$\frac{E_s}{E_k}$
371	0.03	2320	69	0.03
370	0.05	2620	120	0.05
372	0.10	2300	179	0.08
367	0.17	2840	383	0.14
376	0.17	3180	521	0.16
361	0.36	2890	340	0.12
365	0.36	2600	279	0.11

Data concerning angular spray particle energy are listed in Table VII. Plots of the ratio of angular spray particle energy to the kinetic energy of the projectile as functions of exit angle range are shown in Figure 14. The curves in these plots show arbitrary energy distributions which approximately satisfy the values for total spray particle energy given in Table VI and Figure 13. Figure 14 indicates that the bulk of the energy is associated with spray particles coming from the crater at exit angles from about 40 degrees to 70 degrees. This agrees with the results of the work of Turner and Palmer[1] in which similar measurements were made with lead targets and steel projectiles.

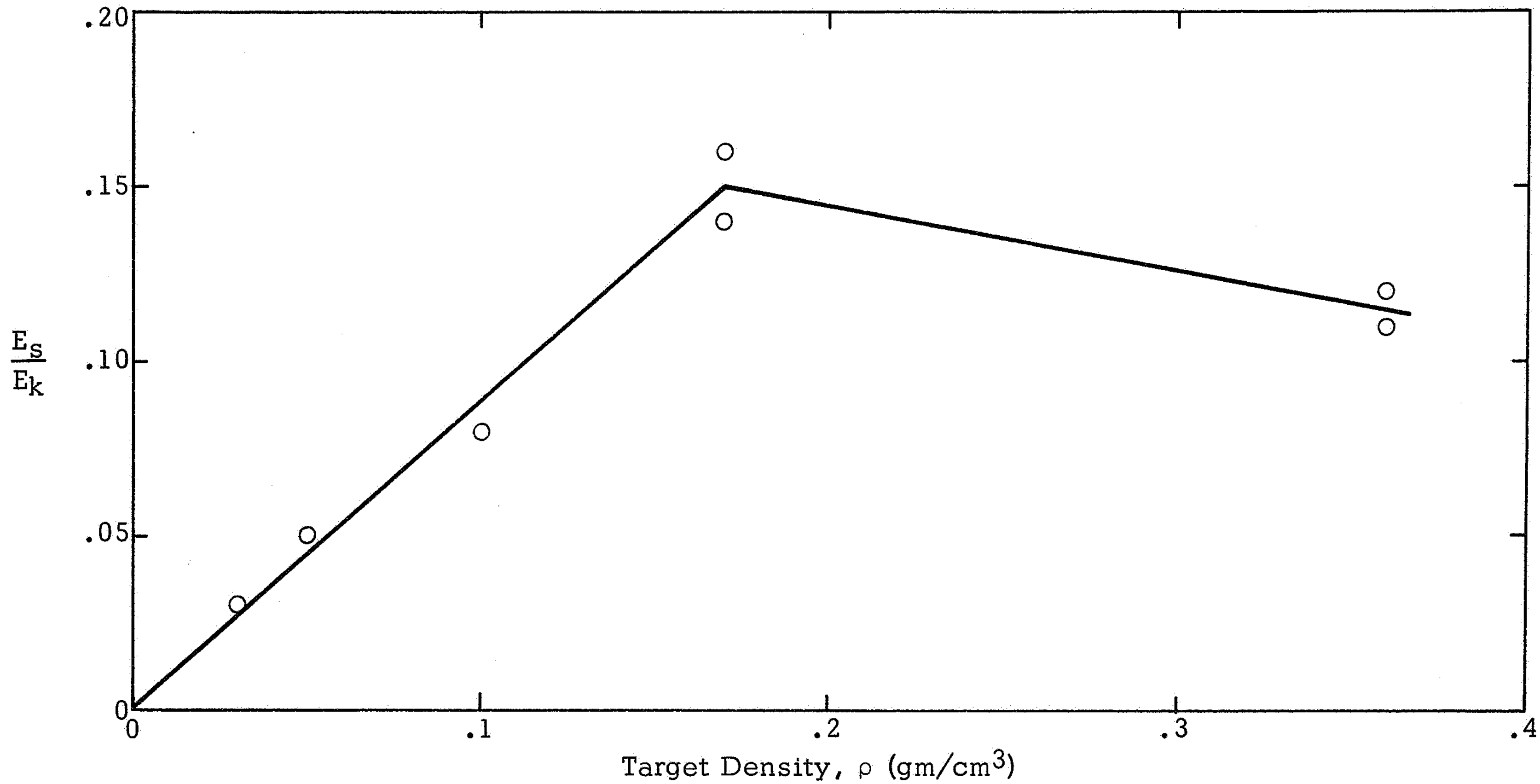

Figure 13. The Ratio of Total Spray Particle Energy, E_s, to the Kinetic Energy of the Projectile, E_k, Plotted as a Function of Target Density for Rigid Polyurethane Foams

TABLE VII. DATA CONCERNING THE ENERGY OF SPRAY PARTICLES LEAVING THE CRATER AT DIFFERENT EXIT ANGLES FOR THE IMPACT OF 3/16-INCH DIAMETER EPOXY-GOLD PROJECTILES INTO RIGID POLYURETHANE FOAMS OF VARIOUS DENSITIES

Shot Number	Target Density (gm/cm^3)	Exit Angle Range (degrees)	Projectile Kinetic Energy, E_k (Joules)	Angular Spray Particle Energy, $E_{s\theta}$ (Joules)	$\frac{E_{s\theta}}{E_k}$
357	0.03	52.5-57.5	2960	74	0.025
394	0.03	50-55	2500	13	0.005
395	0.03	60-65	2530	11	0.004
356	0.05	47.5-52.5	2800	26	0.009
392	0.05	60-65	2320	48	0.021
393	0.05	50-55	2520	38	0.015
373	0.10	50-55	2540	90	0.035
375	0.10	35-40	2170	6	0.003
387	0.10	65-70	2470	36	0.015
390	0.10	60-65	2710	27	0.010
355	0.17	55-60	2610	45	0.017
358	0.17	60-65	2380	100	0.042
384	0.17	45-50	2700	36	0.013
386	0.17	65-70	2470	48	0.019
354	0.36	55-60	2820	55	0.020
379	0.36	50-55	2400	43	0.018
380	0.36	50-55	2500	31	0.012
382	0.36	55-60	2750	45	0.016
396	0.36	60-65	2200	34	0.016

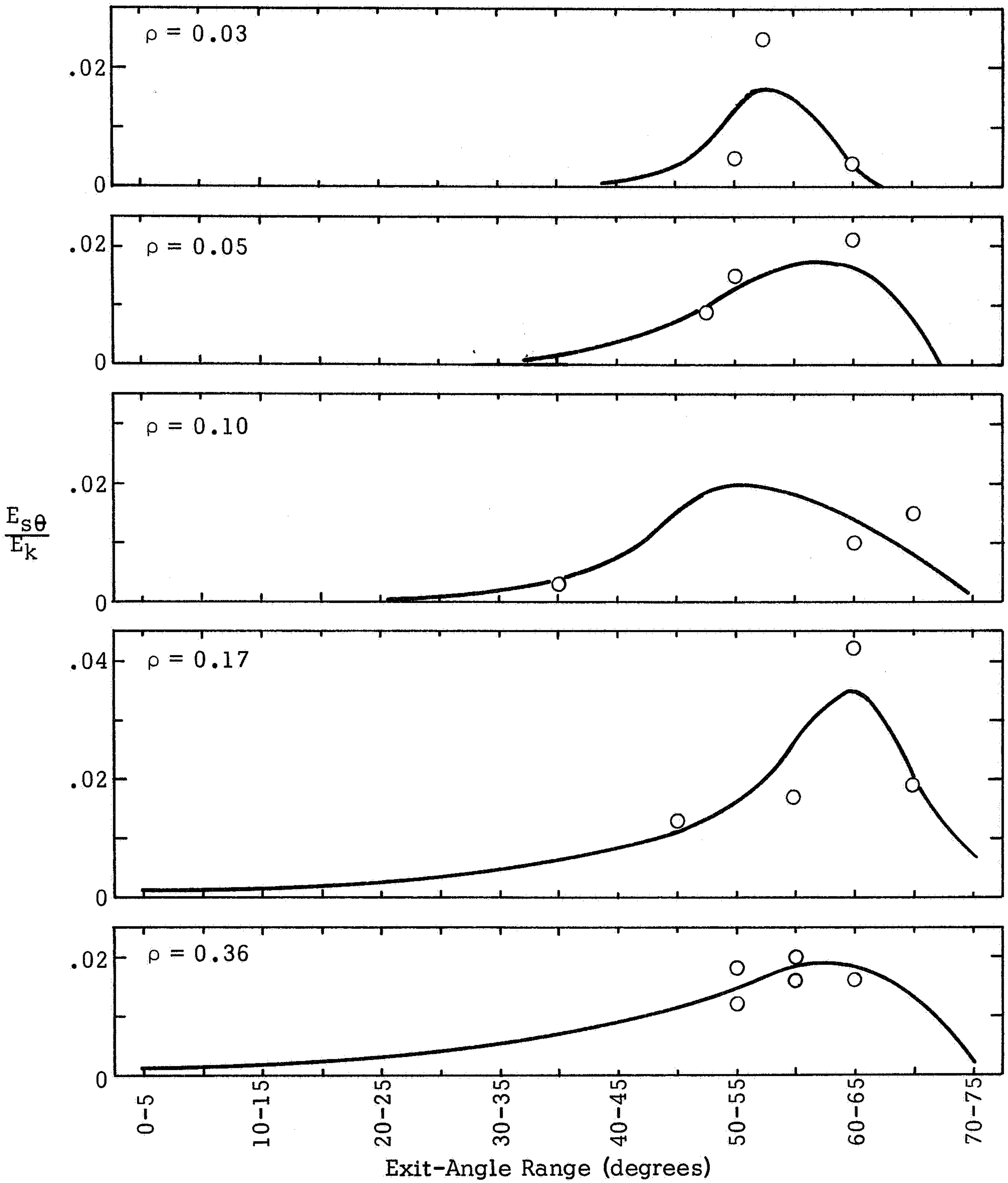

Figure 14. The Ratio of Angular Spray Particle Energy, $E_{s\theta}$, to the Kinetic Energy of the Projectile, E_k, as Functions of Exit-Angle Range for Rigid Polyurethane Foams of Various Densities

Velocity of Ejected Material

Data concerning the average velocity of material ejected from foam targets are listed in Table VIII. Only seven shots were made in which data were obtained. No real analysis can be made of spray particle velocities from these values. The only significant statement that can be made is that there are no indications of large amounts of target material being ejected from the crater at velocities much greater than one kilometer per second.

TABLE VIII. DATA CONCERNING THE AVERAGE VELOCITY OF MATERIAL EJECTED FROM CRATERS FORMED IN RIGID POLYURETHANE FOAM TARGETS BY THE IMPACT OF 3/16-INCH DIAMETER EPOXY-GOLD PROJECTILES. THE BALLISTIC PENDULUM WEIGHED 29.4 GRAMS

Shot Number	Target Density (gm/cm^3)	Exit Angle Range (degrees)	Weight of Particles Caught (grams)	Momentum of Particles (g-cm/sec)	Average Velocity of Particles (km/sec)
394	0.03	60-65	0.037	1710	0.46
393	0.05	60-65	0.007	722	1.03
375	0.10	55-60	0.010	1130	1.13
387	0.10	45-50	0.041	1130	0.28
390	0.10	50-55	0.101	1420	0.14
384	0.17	65-70	0.020	364	0.18
386	0.17	45-50	0.008	157	0.20

Angular Distribution of Ejected Material

Data concerning the mass of material ejected from craters formed in foam targets are listed in Table IX. Figure 15 shows mass of ejecta plotted as a function of exit-angle range for the various target densities. The tendency for material to be concentrated in rays as it leaves the crater might account for the scatter in the data. The curves shown in Figure 15 are not intended to satisfactorily describe all the data. They are included only to show arbitrary distributions which approximately satisfy average values of target mass displaced by the

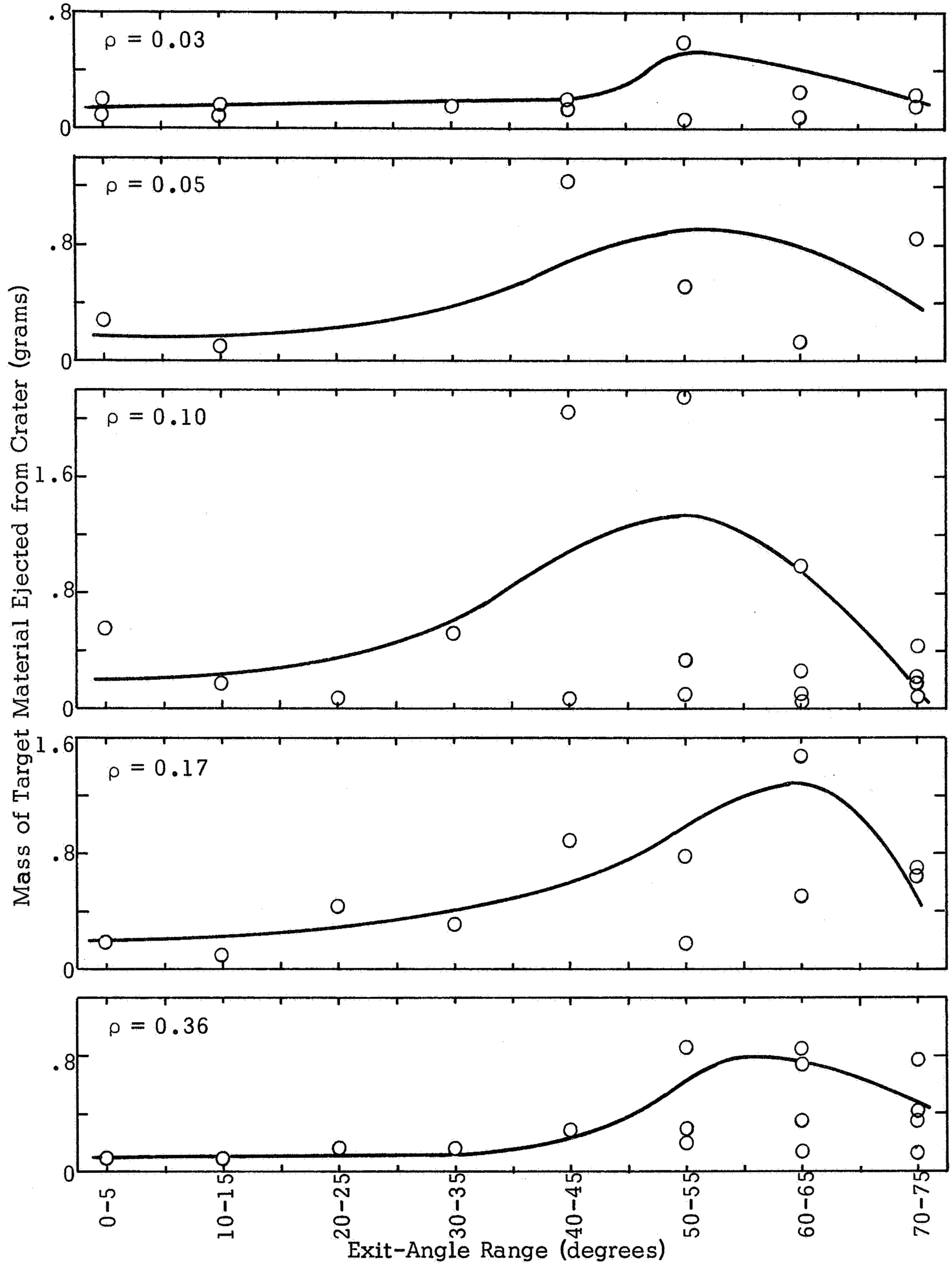

Figure 15. Mass of Target Material Ejected from Crater as Functions of Exit-Angle Range for Rigid Polyurethane Foams of Various Densities

crater as given in Table V. The results shown in Figure 15 are in agreement with those shown in Figure 14 in that the bulk of both the mass and the energy of the ejecta are concentrated between angles of about 40 to 70 degrees.

TABLE IX. DATA CONCERNING THE MASS OF MATERIAL EJECTED FROM CRATERS FORMED IN RIGID POLYURETHANE FOAMS OF VARIOUS DENSITIES BY THE IMPACT OF 3/16-INCH DIAMETER EPOXY-GOLD PROJECTILES

Shot Number	Target Density (gm/cm^3)	Mass of Material Ejected from Crater at Various Angles							
		0-5	10-15	20-25	30-35	40-45	50-55	60-65	70-75
394	0.03	0.19	0.17	--	--	0.14	0.59	0.26	0.23
395	0.03	0.09	0.09	--	0.16	0.20	0.06	0.08	0.15
393	0.05	0.28	0.09	--	--	1.24	0.51	0.13	0.85
373	0.10	0.56	0.18	0.08	0.53	2.04	2.18	0.99	0.43
375	0.10	--	--	--	--	--	0.11	0.04	0.08
387	0.10	--	--	--	--	0.07	0.10	0.26	0.17
390	0.10	--	--	--	--	--	0.34	0.10	0.22
384	0.17	--	0.09	--	--	--	0.17	0.50	0.70
386	0.17	0.19	0.09	0.42	0.30	0.89	0.78	1.47	0.65
379	0.36	--	--	--	--	--	0.20	0.35	0.36
380	0.36	--	--	--	--	--	0.86	0.13	0.13
382	0.36	0.09	0.09	0.17	--	0.28	0.29	0.74	0.43
396	0.36	0.09	0.09	--	0.16	0.28	0.29	0.84	0.78

Specific Energy of Ejected Material

The specific energy of material ejected from foam targets was approximated by dividing values given for the ratio E_s/E_k, from Table VI, by average values of cratering efficiency shown in Figure 12. These numbers are listed in Table X. Figure 16 shows specific energy of ejecta plotted as a function of target density. A straight line through the data indicates that the average specific energy of ejecta is directly proportional to target density, the proportionality constant being about 180 Joules/gram per unit of density.

TABLE X. DATA CONCERNING THE SPECIFIC ENERGY OF MATERIAL EJECTED FROM CRATERS FORMED IN RIGID POLYURETHANE FOAM TARGETS BY THE IMPACT OF 3/16-INCH DIAMETER EPOXY-GOLD PROJECTILES

Target Density (gm/cm^3)	$\frac{E_s}{E_k}$	Cratering Efficiency M_s/E_k (grams/Joule)	Specific Energy of Ejecta E_s/M_s (Joules/gram)
0.03	0.03	1.8×10^{-3}	17
0.05	0.05	2.7	19
0.10	0.08	4.1	20
0.17	0.15	3.7	41
0.36	0.12	1.6	75

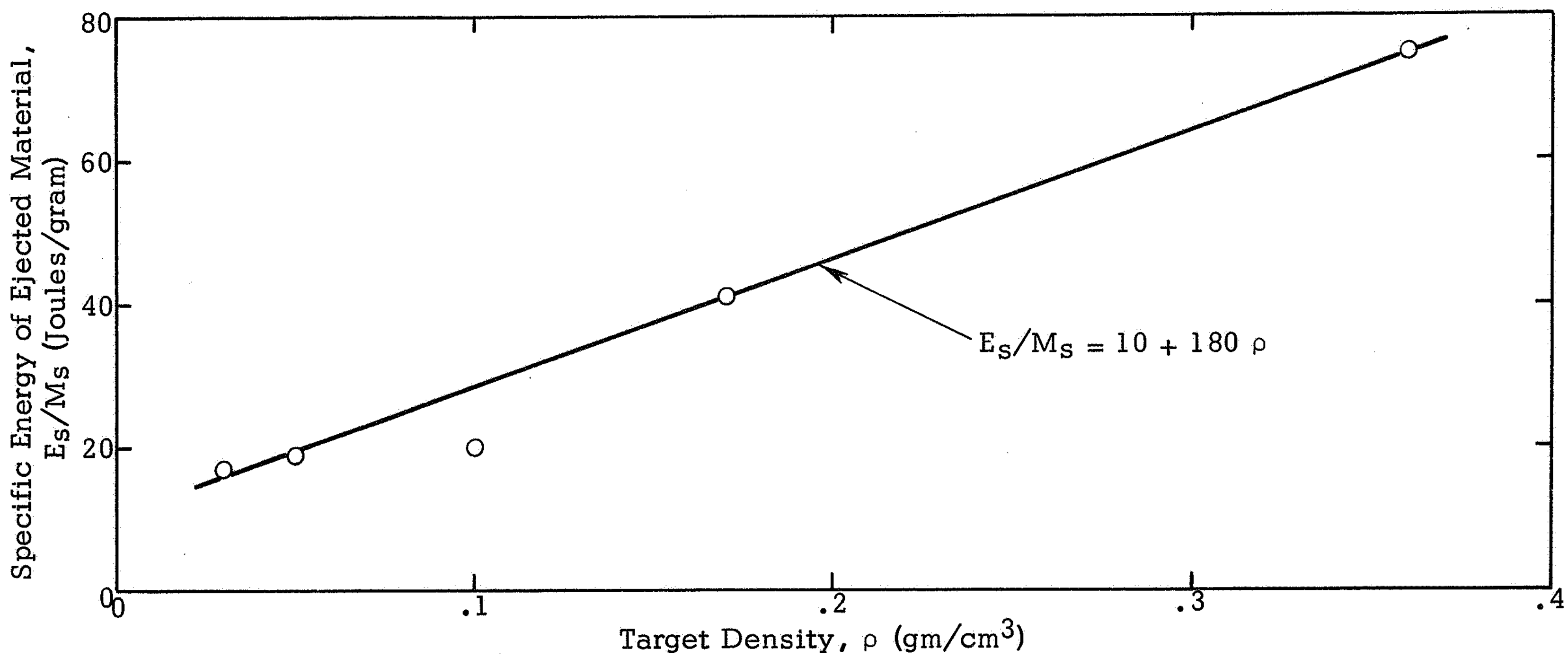

Figure 16. Specific Energy of Ejected Material as a Function of Target Density for Craters Formed in Rigid Polyurethane Foam Targets

CONCLUSIONS

Capture of the Projectile by the Target

At a velocity of six kilometers per second, weak projectiles are poorly retained by foam targets having a density above about 0.1 gm/cm^3. Only with foams with a density of about 0.015 gm/cm^3 would the fraction of the ball captured approach unity. It is expected that faster projectiles, having many times the energy required to vaporize themselves, would be even more efficiently ejected regardless of projectile material. The results indicate that meteor material is unlikely to be found around craters in foam.

Much of the projectile material is retained by targets of very pure aluminum. The hydrodynamic theory indicates that the character of impacts changes slowly in the range 6 - 100 km/sec and it appears likely that much of the meteor will be found distributed over the surface of a soft aluminum crater, and can be examined by neutron activation analysis.

Mass and Velocity of Ejected Material

The bulk of material ejected from a crater, formed in a foam target by a low density projectile impacting at six kilometers per second, leaves at angles of from about 40 to 70 degrees. The bulk of the total energy associated with ejected material is also found at these angles. Particles leaving at these angles have velocities of less than one kilometer per second. Foams of all densities investigated show approximately the same angular distribution of mass and energy of ejecta. The average specific energy of ejecta increases linearly with target density. This suggests that the average velocity of ejecta also increases with increased target density. On the basis of the relationship shown in Figure 16, and assuming that all the energy measured is kinetic, a target density of about 2.8 gm/cm^3 would be required in order that the ejecta have an average velocity of one kilometer per second.

Mass Accretion

The question of whether a body gains or loses mass during a cratering process has been raised. Under the conditions of the experiments described in this work, this question can be answered to some extent by considering two limiting conditions; first, where the target material has a very low density and the projectile is completely captured, and second, where the target material is sufficiently dense that none of the projectile is captured.

In the first condition, an amount of ejected target material equal to that of the projectile must possess the escape velocity of the body being impacted. In the case of the moon where the escape velocity is 2.4 km/sec, the particles would need about 16 percent of the kinetic energy of a 6 km/sec projectile in order to escape. The experiments show that not nearly this amount of energy is available to high velocity particles. In this case the body would gain mass.

In the second case, some mass would be lost. An approximation of the amount can be made by considering Figures 14 and 15. Using these data, the most ideal conditions for escape are with ejecta leaving at angles from 0 to 5 degrees from a foam having a density of 0.36 gm/cm^3. The data in Table II shows that with targets having this density, about 0.006 gram of projectile material remains in the target. Between angles of 0 to 5 degrees, 0.1 gram of material has about 25 Joules of energy. If all of this were kinetic, the particles would have an average velocity of 0.7 km/sec. Under these conditions it is not likely that the body would lose mass. Thus, it appears that in order for a loss of mass to occur, essentially none of the projectile can be captured.